

Wall-to-Bed Mass Transfer in a Fluidized Bed with Twisted Tapes

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Abstract

Wall-to-bed mass transfer coefficients were computed from limiting current measurements made at inner surface of outer cylinder. Glass spheres of three different diameters viz., 3.13, 4.57 and 6.29 mm were used as bed material. An electrolyte belonging to ferricyanide-ferrocyanide redox system has been employed as the liquid phase. In order to investigate the effect of a change in viscosity carboxy methyl cellulose sodium salt (CMC) was used. Twisted tapes of different pitches and widths were employed as internal elements. The experimental study revealed that the presence of twisted tapes in the fluidized bed brought an augmentation of 25 fold over homogeneous flow and 115% over fluidized bed. It was also found that the effect of pitch on mass transfer coefficient was insignificant. The mass transfer coefficient data increased with increment in tape width and particle diameter and decreased with the rise of CMC concentration. The mass transfer coefficient data obtained from the present experiment were correlated to acquire an equation in jD-Re format using least squares regression analysis.

Keywords

Fluidized Bed, Liquid-wall Mass Transfer, Twisted Tape, Mass Transfer Coefficient, Augmentation

Introduction

Fluidized beds hold the advantages of higher heat and mass transfer rates, isothermal conditions and uniform concentrations with better controllability (Kunii and Levenspiel, 1991). Further, enhancement of heat and mass transfer rates is also possible by means of suitable augmentation technique. Various augmentation techniques in practice were categorized into active and passive methods. The active methods require the application of external energy, while as in passive methods augmentation is achieved by modification of the flow passage. Compound augmentation is also often used by combination of the passive and active methods (Bergles, 2003; Dewan et

al., 2004). Employing fluidizing solids for the purpose of enhancing heat or mass transfer coefficients is also recognized as one of the important techniques of augmentation (Jagannadha Raju and Venkata Rao, 1965). The presence of fluidizing solids causes vigorous scouring action that leads to intimate mixing, and hence high heat and mass transfer coefficients are realized. Although there are a large number of studies carried out in heat transfer, a close look at the literature revealed that limited investigations are aimed towards mass transfer.

Among the active augmentative techniques, rotation (Jagannadha Raju et al., 2011) and vibration (Venkateswarlu et al., 2002) are the ones that have attracted the attention of many investigators. A vast majority of investigations aiming at augmentation of heat and mass transfer rates employed mainly passive augmentative techniques. The heat or mass transfer rates are significantly influenced by the thickness of the boundary layer that offers main resistance to the transfer process. These augmentative techniques basically modify the flow path thus intensifying the turbulence which renders the resistance film thin leading to increased heat and mass transfer rates.

Magnitudes of improvements in mass transfer coefficients have been obtained in homogeneous flow in the presence of promoter internals such as string of discs (Venkateswarlu et al., 2000), helical tape on a rod (Sujatha et al., 1997) etc. Significant enhancement has been found in wall-to-bed mass transfer coefficients in fluidized beds with string of discs (Ravi et al., 1996), helicoidal tapes (Jagannadha Raju et al., 2011) etc. Use of internal elements to augment wall-to-bed mass transfer coefficients in gas-liquid-solid fluidized beds (Ramesh et al., 2009) has also been reported. In all these investigations, the liquid-wall mass transfer has been measured using limiting current technique (Lin

et al., 1951). The twisted tape as a displaced promoter internal was found to be effective in heat transfer rate enhancement and several investigations have been reported in this direction (Murty et al., 2009). The importance of twisted tape as an augmentative device has also been emphasized by Murty et al (2009).

Subramanyam et al (2011a) obtained mass transfer coefficients between a flowing liquid and a column wall of an electrochemical cell in the presence of twisted tapes with different widths and pitches as insert promoter elements. The used liquid was an electrolyte belonging to the ferri-ferrocyanide redox system. An increment in tape width resulted in an increment in mass transfer coefficient; while an increase in tape pitch and CMC concentration yielded a decrease in mass transfer coefficient. Subramanyam et al (2011b) carried out studies on pressure drop and bed porosity in fluidized beds with twisted tape internals. The effect of liquid velocity, particle diameter, tape width and tape pitch has been investigated. Correlations were developed for modified friction factor and bed porosity as functions of particle Reynolds number, Froude number, tape width and tape pitch. However, investigations employing twisted tape for enhancement of mass transfer rates in fluidized beds were found to be scarce.

In view of this, the present study has attempted to investigate the effect of liquid velocity, liquid viscosity, tape width, tape pitch and particle diameter on column wall-to-bed mass transfer coefficient in the presence of twisted tape promoter in a fluidized bed. The range of variables covered in the present investigation was compiled in table 1.

TABLE 1 RANGE OF VARIABLES COVERED IN THE PRESENT INVESTIGATION

S.No.	Name of the variable	Min	Max
1	Liquid velocity (cm/s)	4.0	22.8
2	Pitch of the twisted tape (cm)	11.0	∞
3	Width of the twisted tape (cm)	2.0	6.0
4	Diameter of the glass ball (mm)	3.13	6.29
5	CMC concentration (wt%)	0.0	0.3

Experimental Setup Description and Procedure

The equipment was designed and fabricated to carry out studies on wall-to-bed mass transfer at the inner

surface of the outer column of an annular electrochemical cell. The schematic of the experimental set-up used in the present studies was shown in FIG.1. The equipment and apparatus consisted of a cylindrical storage tank (S), centrifugal pump (P) for circulating the electrolyte, two rotameters (R_1 & R_2) to measure the flow rate of the electrolyte, a nitrogen cylinder (N) for supply of nitrogen gas, a U-tube differential manometer (M) to measure the pressure difference across the test section (B). Valves V_1 to V_6 were used to control the flow rates of liquid electrolyte through the experimental column.

The storage tank was of 100 liters capacity, completely covered with an ebonite sheet in order to eliminate contact of electrolyte with the surrounding air. The bottom side of the tank was connected to the suction side of the pump (P) through a globe valve (V_1). Another globe valve (V_2) was provided at the bottom of the storage tank to facilitate the periodic cleaning. A spiral coil (CC) with perforations was placed in the storage tank for deaeration of the electrolyte with nitrogen gas. The deaeration of the electrolyte is required to eliminate the presence of dissolved oxygen because its presence leads to reduction of ferricyanide ion. The discharge end of the pump was divided into two lines, one directly connected to two rotameters (R_1 & R_2) and the other to a by-pass line that was provided with a globe valve V_3 to control the flow through the column. The rotameters were provided which have a combined range of 0 to 64 liters per minute. Two more

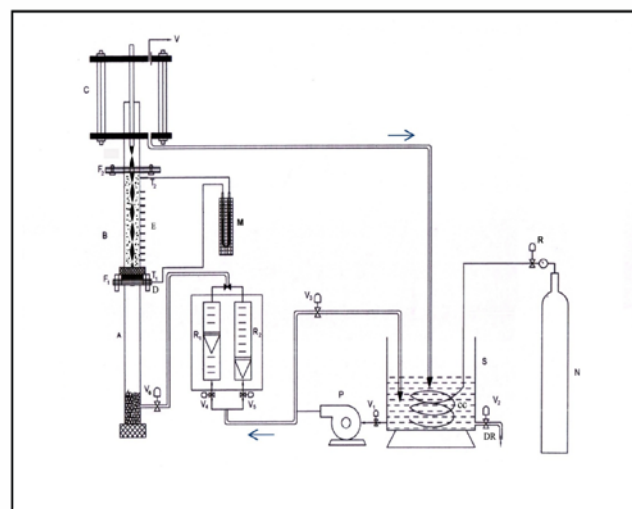


FIG.1: SCHEMATIC OF EXPERIMENTAL UNIT

A – entrance calming section, B – test section, C – exit section, D – distributor, DR – drain, E – point electrodes, F_1 & F_2 – flanges, M – manometer, N – nitrogen gas cylinder, P – pump, R – gas regulator, S – storage tank, CC – spiral coil, T_1 & T_2 – pressure tapings, V – vent, V_1 to V_6 – valves

valves V_4 and V_5 were placed at the entry point of rotameters to operate the rotameters either separately or in combination. Valve V_6 provided at the discharge end of the rotameters facilitated the flow of electrolyte to flow through the experimental column.

The experimental column mainly consisted of three sections: an entrance calming section (A), a test section which is the fluidizing section (B) and an exit section (C). The entrance calming section (A) made of a copper tube of 6.73 cm inner diameter and 1.07 m length, was filled with marble stones of random size, to eliminate the effects due to tangential entry of the fluid electrolyte and to minimize the fluctuations. Section A was connected to the main test section (B) by means of a flange (F_1). The test section (B), which served as a fluidizing column, was made of smooth perspex tube of 6.73 cm inner diameter and 0.6 m height. The inner wall of the test section was provided with 34 copper point electrodes of diameter 3.42 mm. One end of these electrodes was fixed flush with the surface of the inner wall of the test section while the other end projected outward served as terminal to connect the electrodes to the external circuit. Two pressure taps, (T_1) at the bottom flange and (T_2) at the top flange have been provided across the test section for pressure drop measurements. These taps were connected to the limbs of the U-tube manometer to measure the pressure drop. Carbon tetrachloride was used as manometric fluid. A stainless steel wire mesh (D) was placed at the bottom of the test section to support the bed of solids and allow the uniform distribution of liquid electrolyte. The promoter element was essentially a copper twisted tape of given width w , thickness t with a desired pitch p as shown in FIG.2. The exit section (C) was also of the same diameter as A and B with its open end into the atmosphere. Section C was connected to the test section (B) by means of a flange F_2 . The liquid electrolyte from the exit section was drawn from the bottom.

Limiting current measurements for the case of reduction of ferricyanide at copper point electrodes fixed flush with the inner surface of an outer annulus. The ferricyanide-ferrocyanide redox system has been chosen for these studies because the chemical polarization involved is negligible, the reacting surface remains smooth and unaffected, and the measurements are relatively fast, accurate and reproducible. The electrode reaction involved in this study is

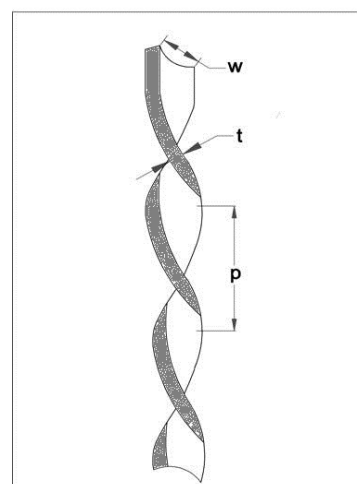
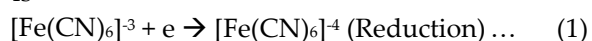


FIG.2: SCHEMATIC OF TWISTED TAPE – PITCH; W- WIDTH; T – THICKNESS

About 80 liters of equimolar solution of potassium ferrocyanide and potassium ferricyanide of 0.01 N and 0.5 N of sodium hydroxide were prepared from analytical grade reagents using distilled water and this solution was used as the electrolyte. The rotameters were calibrated using this fluid electrolyte. The solution was deaerated using nitrogen prior to recirculation through the test section. In presence of CMC, the electrolyte was made by using 0.4 N $\text{Na}_2\text{CO}_3/\text{NaHCO}_3$ as indifferent electrolyte in the place of 0.5 NaOH, which is due to the reaction between sodium hydroxide and CMC.

The electrolyte from the storage tank was metered and circulated through the test section. The two rotameters R_1 and R_2 were used to measure the flow rate of electrolyte and the flow rate was adjusted by using the control and pass valves. When the liquid flow rate was stabilized, the limiting current was measured. Subramanyam et al (2011a) described in detail the method of measurement of limiting current. From the measured limiting current value, the mass transfer coefficients were evaluated from the following equation (Lin et al., 1951):

$$k_L = \frac{i_L}{nAFC_0} \quad (2)$$

No longitudinal variation has been found in case of homogeneous flow with twisted tapes as reported by Subramanyam et al (2011a). In the present experiment, limiting currents were measured at each of the 34 electrodes as well. It was found that there was no longitudinal variation in the limiting current values along the test section. Therefore, all the 34 electrodes were combined and limiting current data at this combined electrode were obtained for all subsequent

runs. During each run the reacting ion concentration was obtained by volumetric analysis (Vogel, 1951). The temperature of the electrolyte for each run was measured with the accuracy up to $\pm 0.1^\circ\text{C}$.

The bed materials used in the present investigation were spherical glass balls of different sizes. A known amount of solid particles was charged into the main fluidization column. Bed voidage, ε was determined based on bed height measurements. The bed heights were measured using a pre-calibrated scale provided on the test section. The perspex test section being transparent facilitated the measurement of bed height and the observation of distribution of solids in the bed. The bed voidage was computed as (Subramanyam et al., 2011b)

$$\varepsilon = 1 - \frac{W_s}{\rho_s(V_b - V_p)} \quad \dots (3)$$

Results and Discussion

Initially pressure drop and bed porosity data were obtained from the fluidized bed with twisted tape internals. These data were found to be in good agreement with that of Subramanyam et al (2011b).

Augmentation

FIG.3 gives the data of the present study plotted as mass transfer coefficient k_L against liquid velocity V for four cases of (i) homogeneous liquid flow (Plot A), (ii) homogeneous flow with a twisted tape internal (Plot B), (iii) liquid solid fluidized bed (Plot C), and (iv) liquid-solid fluidized bed with a twisted tape (Plot D). The magnitudes of improvements over homogeneous liquid flow were shown through plots B, C and D. Plot A is the data predicted based on Lin et al (1951) for the case of homogeneous liquid flow (empty conduit flow). Plot B is the present experimental mass transfer coefficient data in homogeneous flow in the presence of a twisted tape $\{p = 86 \text{ cm}; w = 2 \text{ cm}\}$. This data is in agreement with that of Subramanyam et al (2011a). The present data on liquid-solid fluidized bed are shown as Plot C. This data confirmed that of the data of Jagannadha Raju and Venkata Rao (1965) with 8% deviation. Plot D shows the data in liquid-solid fluidized bed in the presence of a twisted tape promoter $p = 86 \text{ cm}; w = 2 \text{ cm}\}$. Plots A and B show that the improvements in the mass transfer coefficients due to twisted tape in an otherwise homogeneous flow were up to a maximum of 8 fold. The improvements due to the presence of twisted tape promoter in a liquid-solid fluidized bed were up to 115 percent over

that without using a promoter (Plots C and D). Plot D gives the magnitudes of augmentation in mass transfer coefficient in liquid-solid fluidized bed with twisted tape increased by 200 percent over homogeneous flow with twisted tape (Plots B and D). The plots reveal that highest coefficient could be realized in a three-phase fluidized bed with a turbulent promoter. Twisted tape promoter in a liquid-solid fluidized bed was found to show an augmentation in the mass transfer coefficient up to a maximum of 25-fold over that of empty conduit flow (Plots D and A). These observations indicate that the introduction of twisted tape into a liquid-solid fluidized bed (Plot D) is definitely advantageous as it enhances turbulence resulting in increased mass transfer. Moreover, swirl flow may be visualized when a twisted tape promoter is inserted into the axial flow through a conduit. The generated swirl due to the flow of the fluid past the boundaries of the twisted tape element induces its radial component into the axial flow. As the axial flow is increased, the radial component progressively moves towards the confining wall, resulting in a tractive shear along the wall over which the transfer reactions (red-ox) take place. The turbulent mixing of the fluid elements is thus, expected to contribute to higher augmentation in the mass transfer coefficients at the confining wall, which is evident from Plots B and D of fig.3. Augmentation of the wall mass transfer coefficients can be attributed to the effective reduction in the boundary layer thickness due to the prevailing tractive shear at the electrode surface. The combined effect of swirl flow superimposed on the complex phenomena of liquid-solid fluidization would also contribute to the reduction in the boundary layer thickness considerably.

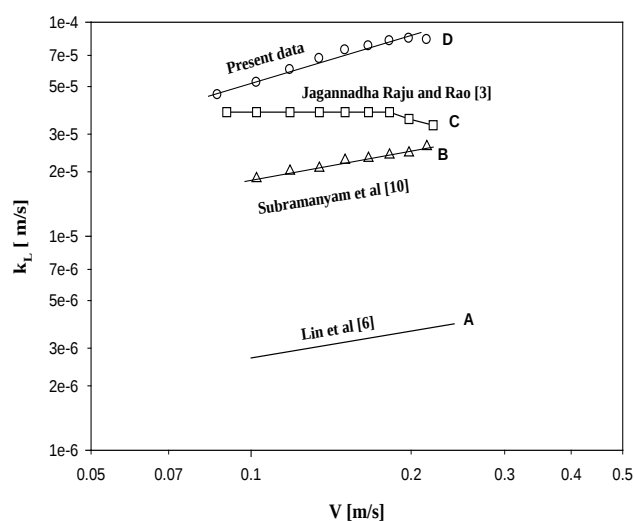


FIG.3: AUGMENTATION WITH TWISTED TAPE

Effect of Pitch on k_L

The mass transfer coefficient data obtained from the present experiment have been plotted against liquid velocity for a constant tape with width 2 cm and varying pitch as shown in FIG.4. It can be observed from the plots of the figure that the mass transfer coefficient increased with liquid velocity and approached a constant value. It is well established that the main resistance to mass transfer is the thickness of the resistance film formed on the transfer surface. Increase in turbulence decreases the thickness of the film, leading to increased mass transfer (Ramesh et al, 2009). In the present case, turbulence is generated by flowing liquid, twisted tape and fluidizing solids. It can be understood that the total turbulence rises initially with an increase in liquid velocity and reaches maximum. Further increase in liquid velocity cannot add further turbulence. Therefore, the mass transfer coefficient initially increased and then approached a maximum value. Further, the plots of the figure revealed that the tape pitch had no discernible effect on mass transfer coefficient. The turbulence generated by tapes with different pitches may be insignificant when compared with the turbulence generated by other modes. Therefore, insignificant effect of tape pitch on mass transfer coefficient was noticed. Similar observations can also be made from FIG.5 which was drawn between k_L and V for varying tape pitches with a constant tape width of 4 cm in 4.57 mm particle bed.

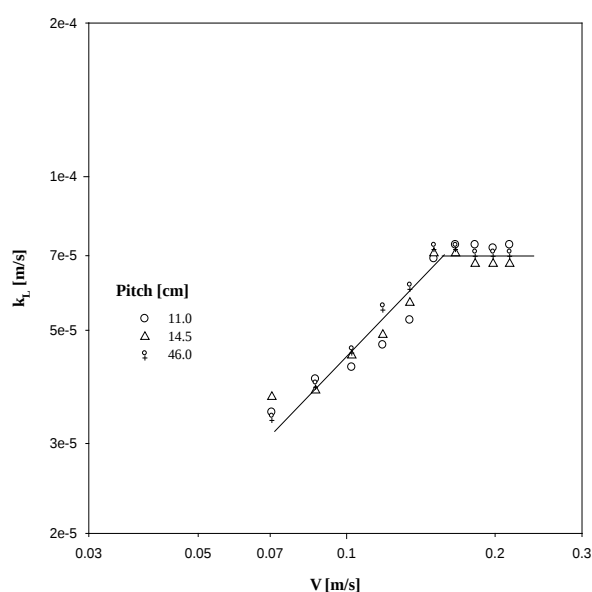


FIG.4: EFFECT OF PITCH: VARIATION OF MASS TRANSFER COEFFICIENT IN A FLUIDIZED BED OF 4.57 MM PARTICLES WITH TWISTED TAPES OF CONSTANT WIDTH 2 CM

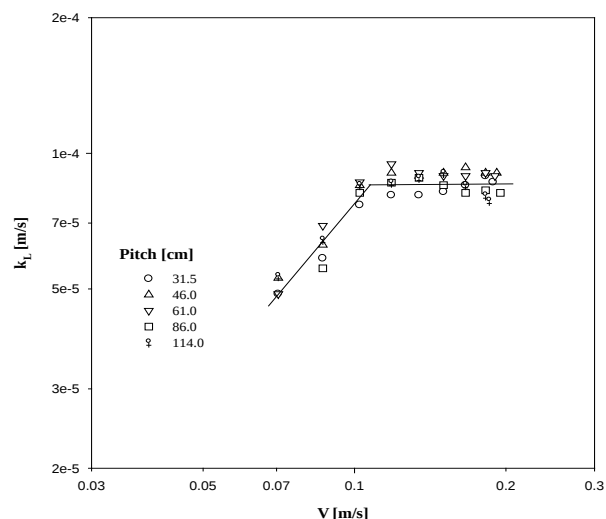


FIG.5: EFFECT OF PITCH: VARIATION OF MASS TRANSFER COEFFICIENT IN A FLUIDIZED BED OF 4.57 MM PARTICLES WITH TWISTED TAPES OF CONSTANT WIDTH 4 CM

Effect of Tape Width on k_L

The mass transfer coefficient data obtained for three different tape widths at a constant tape pitch of 86 cm were plotted against liquid velocity and presented in FIG.6. Plot A represents the data of tape width 2 cm, plot B that of 3 cm and plot C for 4 cm. These plots revealed that the mass transfer coefficient increased with liquid velocity and reached a constant value. Further, the higher the tape width is, the higher the mass transfer coefficient is. This observation is also conspicuous from the cross-plot shown as k_L against tape width w , in the inset fig.6a.

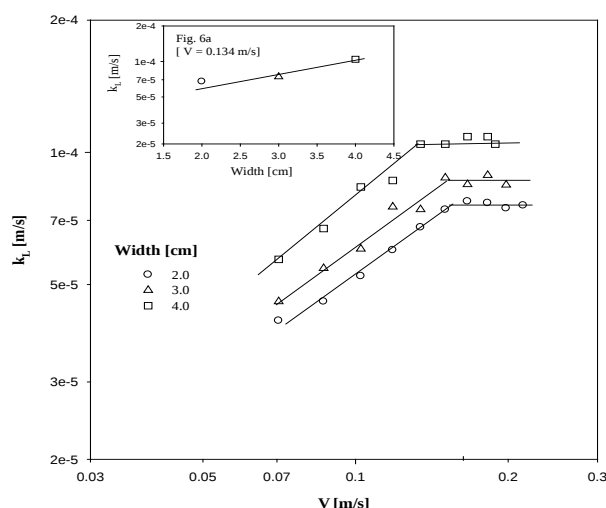


FIG.6: EFFECT OF WIDTH: VARIATION OF MASS TRANSFER COEFFICIENT IN A FLUIDIZED BED OF 4.57 MM PARTICLES WITH TWISTED TAPES OF CONSTANT PITCH 86 CM

It is well understood that the main resistance to the mass transfer is due to the thickness of the fluid film that formed on the transfer surface. The presence of twisted tape, by modifying the flow passage of the fluid, directs the fluid and solid particles towards the inner surface of the test section. The solid particles strike the transfer surface strongly, resulting in decreased thickness of this resistance film. As the liquid velocity is increased, the solids strike the transfer surface with more momentum, further declining the thickness of the resistance film. Hence, the mass transfer coefficient increased with increment of liquid velocity. The mass transfer coefficient reached a maximum value with increase in liquid velocity and remained constant with further increase in liquid velocity. This is because the maximum turbulence has been reached corresponding to those operating conditions. Therefore, the mass transfer coefficient remained constant. With increase in tape width, more liquid and solid particles were driven towards the transfer surface, reducing the thickness of the resistance film. Hence higher mass transfer coefficients were realized with increase in tape width.

Effect of Particle Diameter on k_L

The mass transfer coefficient data obtained from the present experiment were plotted against liquid velocity for a constant tape width of 2 cm and a tape pitch of 16 cm. The electrolyte contained CMC of 0.2 wt%. Three plots obtained for three particles of diameters 3.13, 4.57 and 6.29 mm were shown in FIG.7.

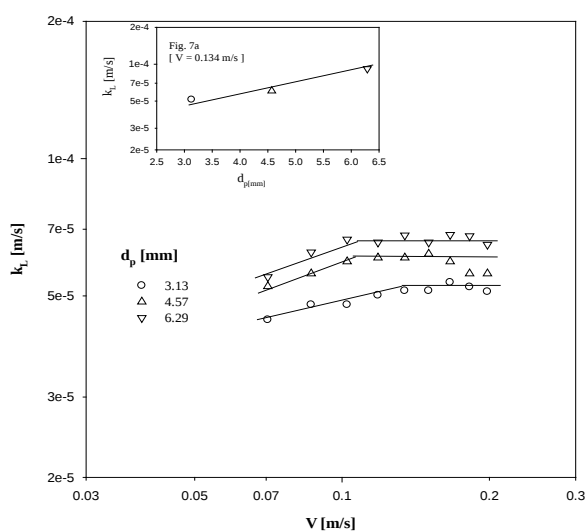


FIG.7: EFFECT OF PARTICLE DIAMETER: VARIATION OF MASS TRANSFER COEFFICIENT IN A FLUIDIZED BED OF WITH TWISTED TAPE [P = 16 CM; W = 2 CM] AND THE CMC CONCENTRATION IS 0.3 WT%

The mass transfer coefficient rose with increasing liquid velocity and attained a constant value with further increase in liquid velocity. The trend is same for all particles. Higher mass transfer coefficient was realized for particles of higher diameter. This is because larger particle strikes the transfer surface very strongly compared to smaller particle, thus reducing the thickness of resistance film. This is also clear from FIG.7a which is inset of FIG.7.

Effect of CMC Concentration or Viscosity

Carboxy methyl cellulose sodium salt (CMC) was added to bring change in viscosity of the electrolyte. Since the presence of sodium hydroxide in the electrolyte reacts with CMC, sodium carbonate and sodium hydrogen carbonate each with 0.4 N were added as inert electrolytes in place of sodium hydroxide. The physical property data for this solution were available in Tonini et al (1978). The mass transfer coefficient data obtained in the presence of a twisted tape of pitch 86 cm and width 4 cm, were shown plotted against liquid velocity in FIG.8. The bed material contained particles of 4.57 mm. Three plots A, B and C were obtained corresponding to the CMC concentrations of 0.1, 0.2 and 0.3 wt%, respectively. It is observed from plot A that the mass transfer coefficient increasing with increment in liquid velocity reached a maximum value and remained constant. Plot B corresponds to a CMC concentration of 0.2 wt%, in which the mass transfer coefficient rose with increasing liquid velocity, remained constant with further increase in liquid velocity and exhibited a decreasing trend further. Because, initially with increasing liquid velocity, the particles strike the transfer surface with increased momentum, incurring decline in the thickness of the resistance film. With further increase in liquid velocity, the turbulence attained is maximum, hence the mass transfer coefficient remained constant. Additional increase in liquid velocity caused more bed expansion, hence the bed became lean, so that less number of particles strike the transfer surface. Therefore, the mass transfer coefficient decreased with increase in liquid velocity. Similar trend was observed from plot C for the case of 0.3 wt% CMC. Besides, addition of CMC makes the solution viscous; and the more CMC concentration is, the more its viscosity is. Increasing viscosity means the rising thickness of resistance film. Therefore, increasing CMC concentration causes a decrease in mass transfer coefficient, which is also evident from FIG.8a.

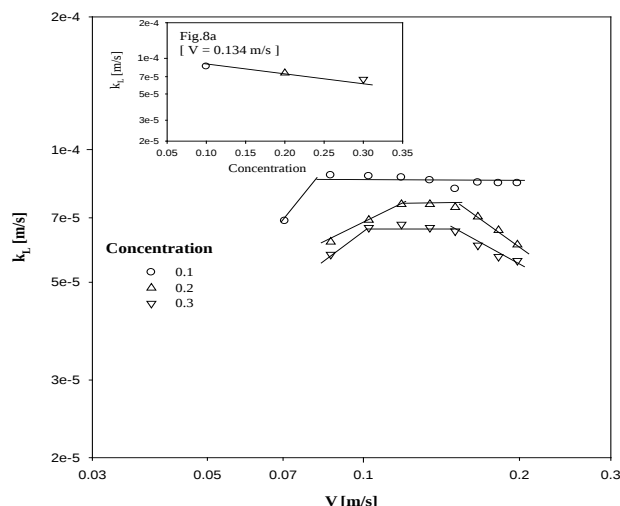


FIG.8: EFFECT OF CMC CONCENTRATION: VARIATION OF MASS TRANSFER COEFFICIENT IN A FLUIDIZED BED OF 4.57 MM PARTICLES WITH TWISTED TAPE { $P = 16$ CM; $W = 2$ CM}

Correlation

The data on mass transfer coefficient obtained from the present experiment have been correlated in j_D -Re format of equation

$$j_D \varepsilon = 0.0116 \left[\left(\frac{Re_p}{1 - \varepsilon} \right) \left(1 + \frac{p}{D_c} \right) \right]^{0.04} \left(1 + \frac{w}{D_c} \right)^{1.39} \quad \dots(4)$$

Average deviation = 9.58%

Standard deviation = 12.81%

The correlation plot is shown in FIG.9.

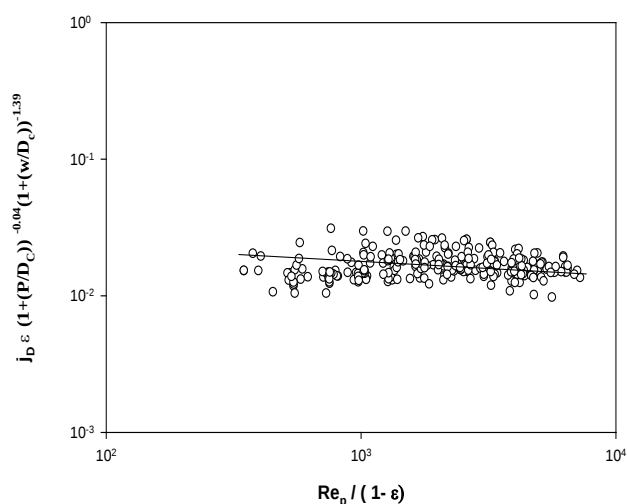


Fig. 9: Correlation plot in accordance with eqn.(4)

Conclusions

Based on 1500 data points, the following conclusions were drawn.

- The mass transfer coefficient was observed to be independent to tape pitch
- The mass transfer coefficient increased up to 40% with increase in tape width from 2 cm to 4 cm
- An increase in particle diameter from 3.13 mm to 6.29 mm caused an increment of 22% mass transfer coefficient
- Increase in CMC concentration from 0.1% to 0.3% decreased the mass transfer coefficient by 24%.

Notations

A	area of the reacting surface [m ²]
C_0	concentration of ferricyanide ion [kmol/m ³]
d_p	particle diameter [m]
D_c	column diameter [m]
D_L	diffusivity of reacting ion [m ² /s]
F	Faraday constant [C/mol of electrons]
i_L	limiting current [A]
j_D	mass transfer factor = $\frac{k_L}{V} Sc^{2/3}$ [-]
k_L	mass transfer coefficient [m/s]
n	number of electrons released or consumed during the reaction [-]
p	tape pitch [m]
Re_p	particle Reynolds number, $\frac{\rho d_p V}{\mu}$ [-]
Sc	Schmidt number = $\frac{\mu}{\rho D_L}$ [-]
t	thickness of the twisted tape [m]
V	liquid superficial velocity [m/s]
V_b	volume of bed [m ³]
V_p	volume of promoter in bed [m ³]
w	tape width [m]
W_s	weight of solids in bed [kg]

Greek symbols

ε	bed porosity [-]
μ	viscosity [kg/m s]
ρ	density of liquid [kg/m ³]
ρ_s	density of solids [kg/m ³]

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